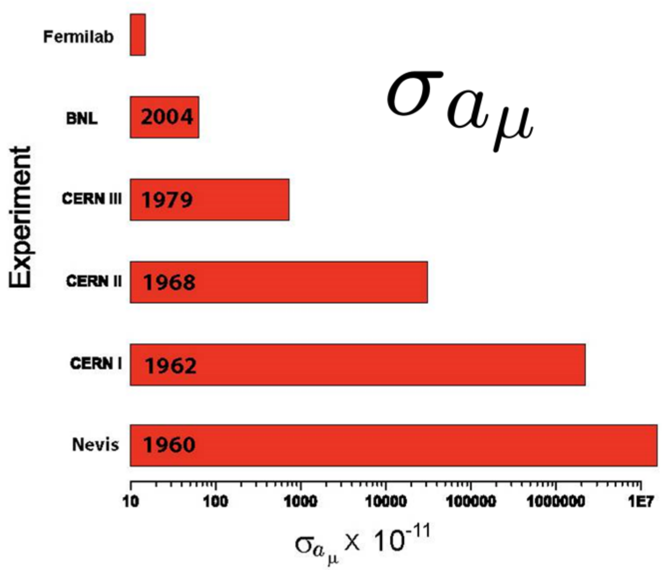
E989: Muon g-2 at Fermilab

David Hertzog, Lee Roberts
Co-Spokespersons
Chris Polly – Project Manager

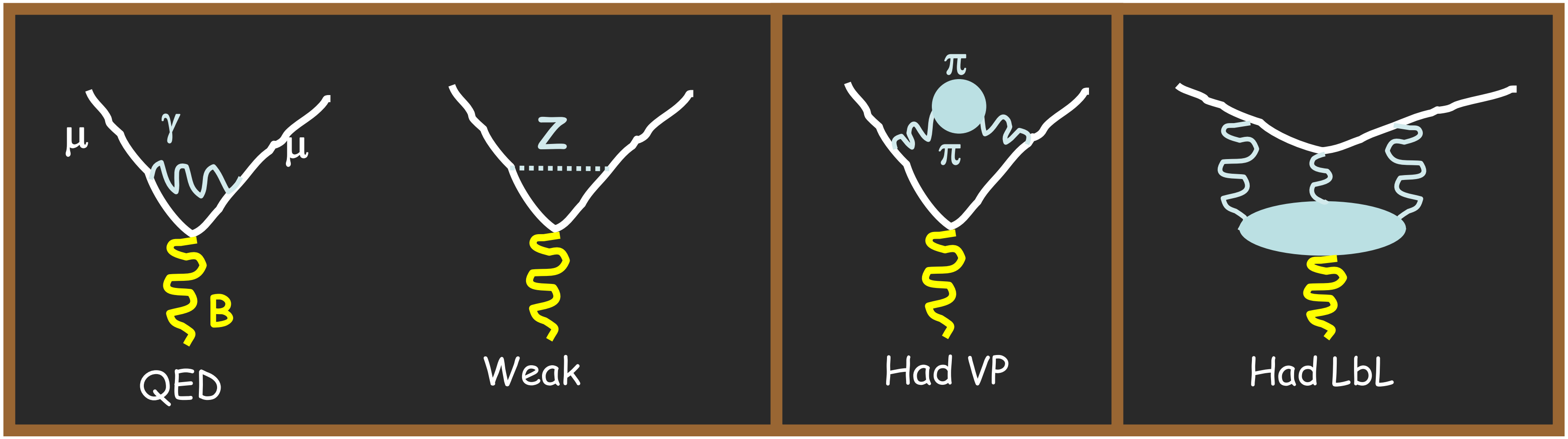
Physics Case

Budgets / Timelines

Special Remarks



$a_\mu = (g-2)/2$ can be calculated and measured very precisely to test the completeness of the SM



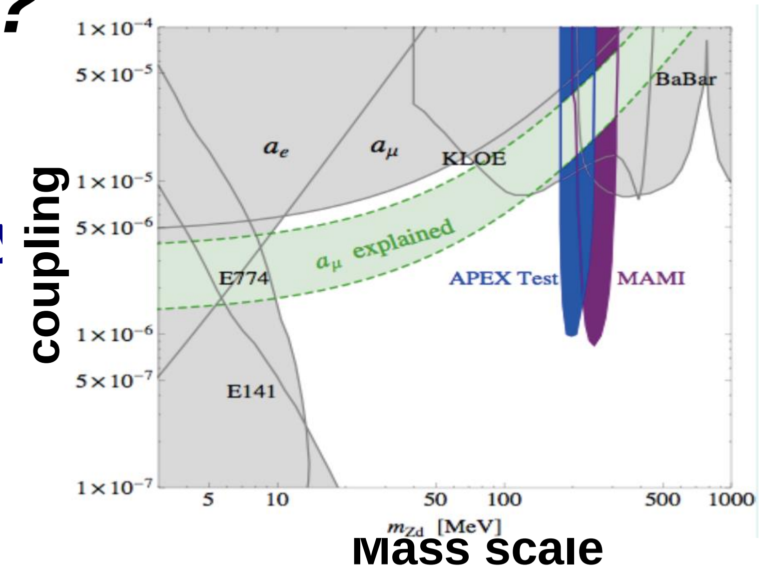
Known well **Theoretical work ongoing**

	VALUE ($\times 10^{-11}$) UNITS
QED ($\gamma + \ell$)	$116\,584\,718.951 \pm 0.009 \pm 0.019 \pm 0.007 \pm 0.077_\alpha$
HVP(lo) [20]	$6\,923 \pm 42$
HVP(lo) [21]	$6\,949 \pm 43$
HVP(ho) [21]	-98.4 ± 0.7
HLbL	105 ± 26
EW	154 ± 1
Total SM [20]	$116\,591\,802 \pm 42_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 49_{\text{tot}})$
Total SM [21]	$116\,591\,828 \pm 43_{\text{H-LO}} \pm 26_{\text{H-HO}} \pm 2_{\text{other}}\ (\pm 50_{\text{tot}})$

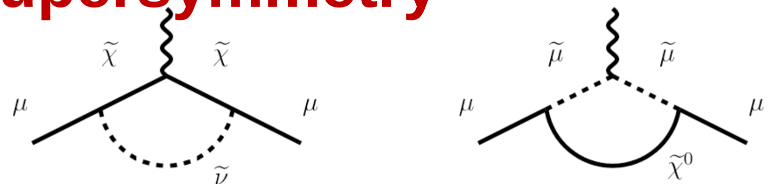
$\Delta a_\mu(\text{Expt} - \text{Thy}) = 287 \pm 80 \times 10^{-11}$ 3.6 σ

New physics enters through *loops*. *What might the g-2 signal imply?*

- **Dark Photons**
  - **light new vector particles V kinetically mixed with the photon**

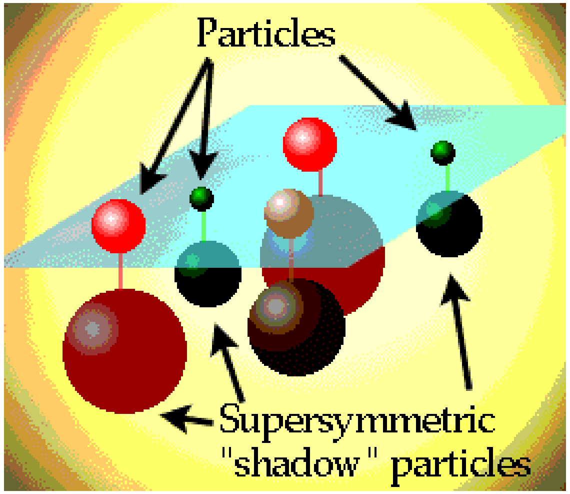


- **Supersymmetry**



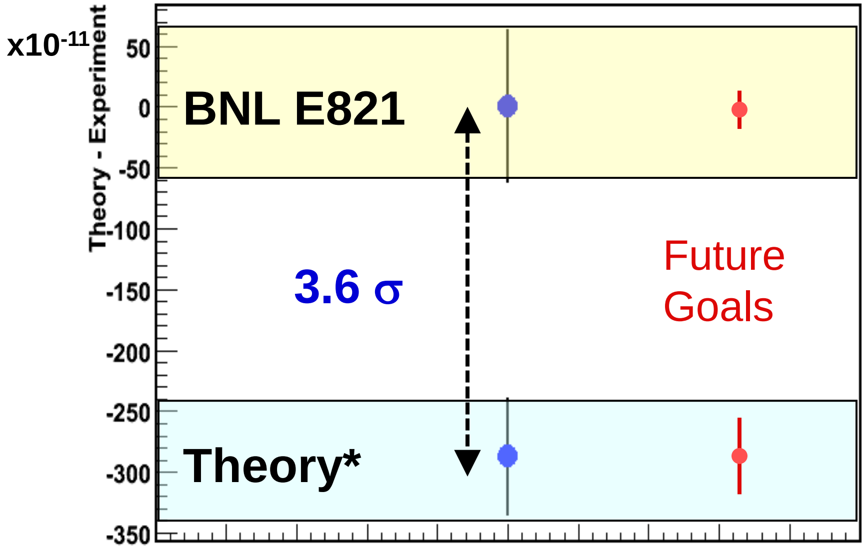
$$\boxed{a_\mu^{SUSY} \approx 130\times10^{-11}\left(\frac{100\ \text{GeV}}{M_{SUSY}}\right)^2 \tan\beta\ \text{sign}(\mu)}$$

Difficult to measure at the LHC



- **The Uninvented**
  - **Perhaps the most important of all**

Our goal is to achieve *Discovery Threshold*
→Fourfold reduction in experimental error



Goal: 140 ppb

7.5 σ if same central values

Expected 330 ppb

E989 Experimental Scope

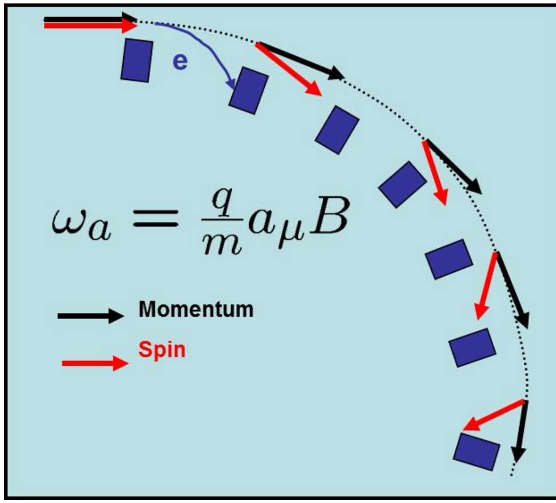
Positive muons will be used to measure the muon anomaly to an absolute precision of $\delta a_\mu = 16 \times 10^{-11}$ (140 ppb). The error budget is distributed as follows:

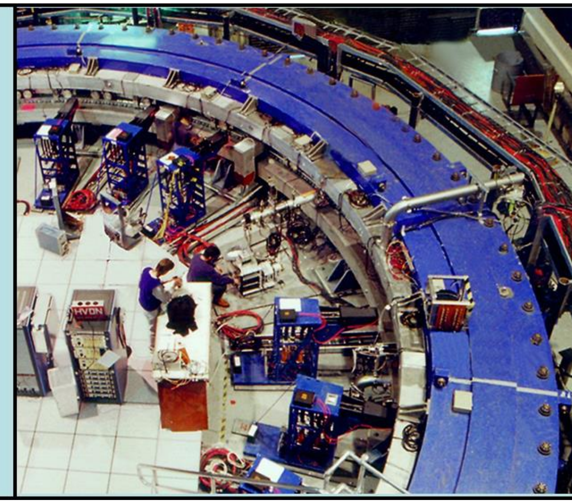
Category	Error (ppb)	vs BNL E821
Statistical	100	x20 events
Field Systematics	70	x2 better
Precession Systematics	70	x3 better

Follow-up run using Negative Muons is a natural next phase

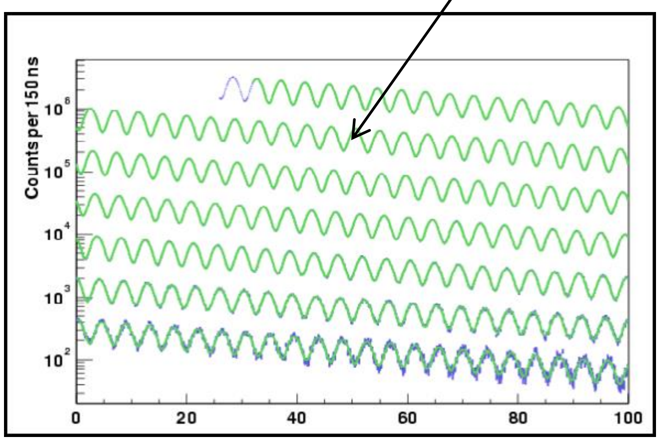
*See Snowmass Review : http://arxiv.org/abs/1311.2198 *The Muon (g-2) Theory Value: Present and Future*

$a_\mu = (g-2)/2$ is derived from the precession of the muon spin in a well-measured magnetic field

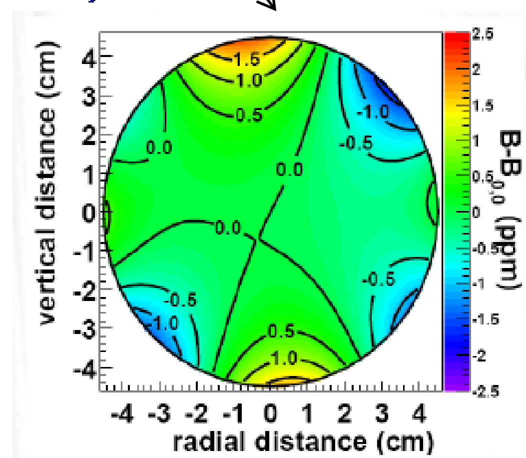




$$\omega_a = \omega_{spin} - \omega_{cyclotron} = \left(\frac{g-2}{2}\right)\frac{eB}{mc}$$



Precession frequency

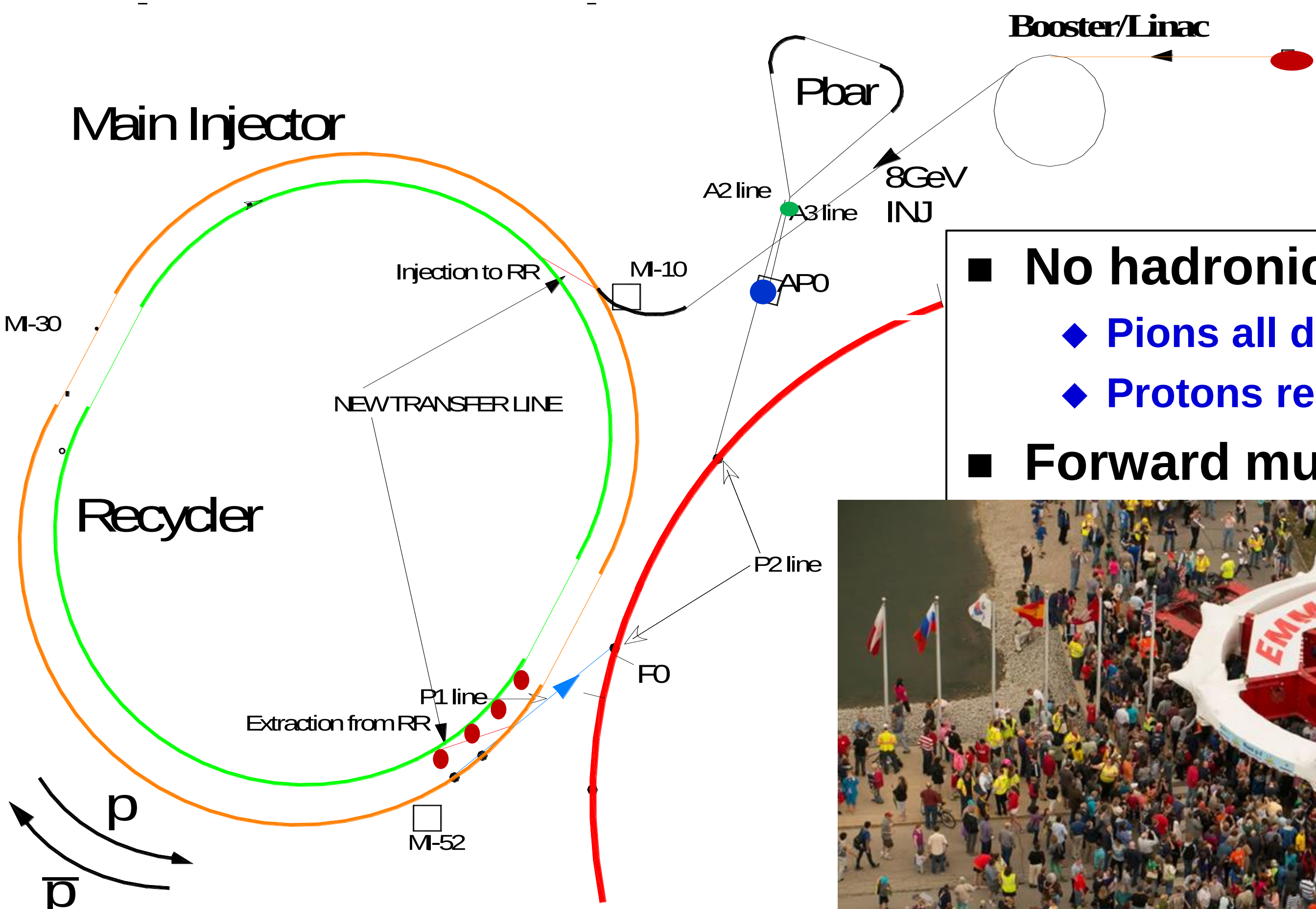


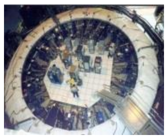
Average Magnetic Field

Five key areas of focus to achieve the precision goal:

1) More Muons, delivered more often to the ring
2) Muon Storage Fraction improvement
3) Better Modeling of stored beam motions
4) Higher Field Uniformity and Monitoring
5) Reduced Precession Frequency Systematics

More Muons: A ~2000 m track at FNAL, filled 2.7 x more frequently allows for much higher μ/p production and overall data collection rate

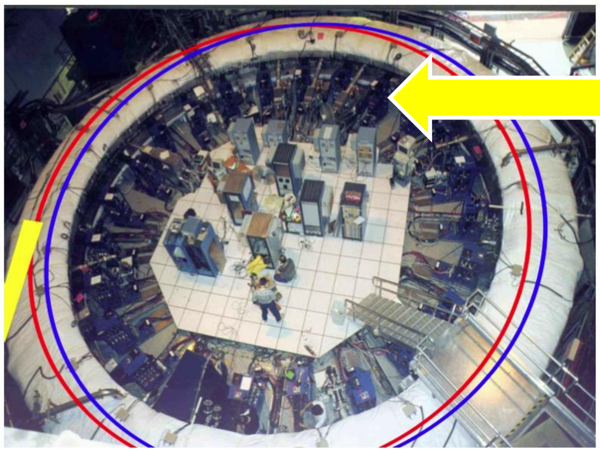




- No hadronic flash
  - Pions all decay
  - Protons removed by a kicker
- Forward muons collected

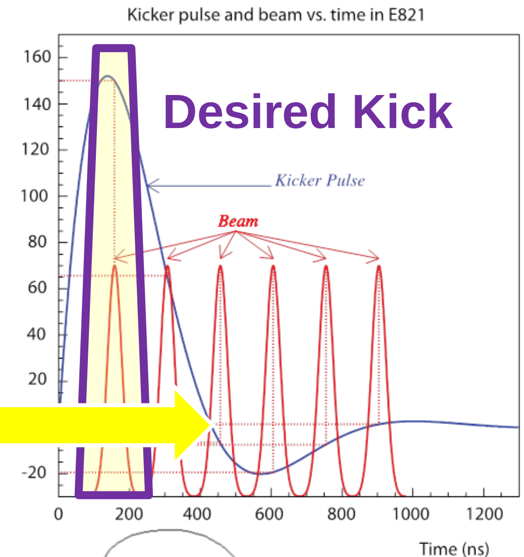
Ring arrives at FNAL

Improved muon Storage Fraction (Kicker, Quads and Inflector Upgrades)

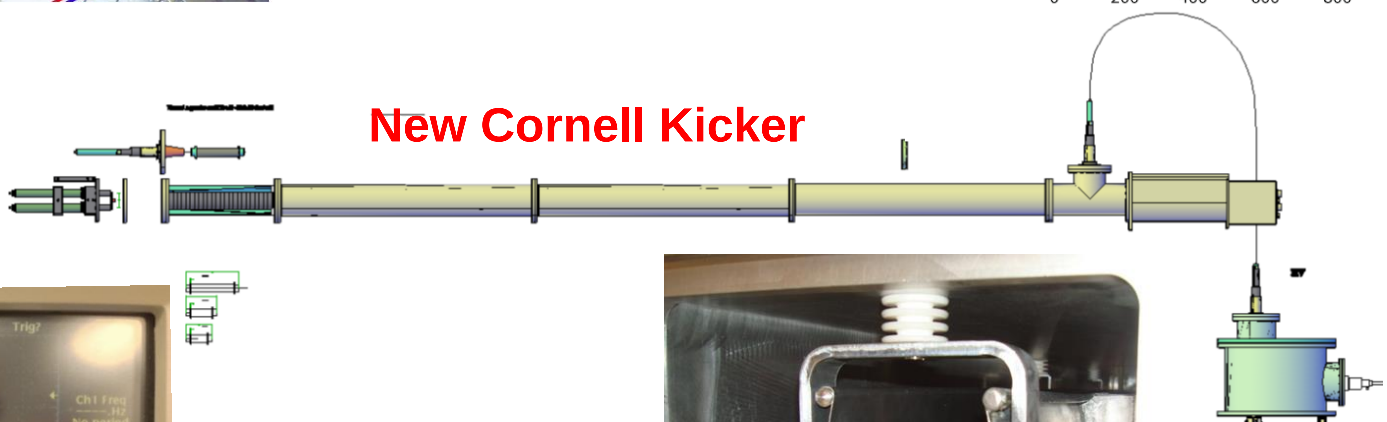


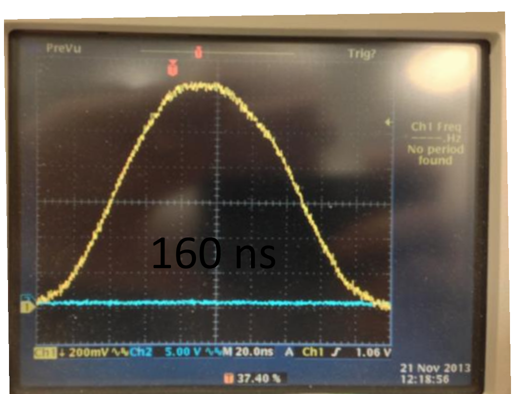
Kicker needed to put Muons onto a Stable Orbit

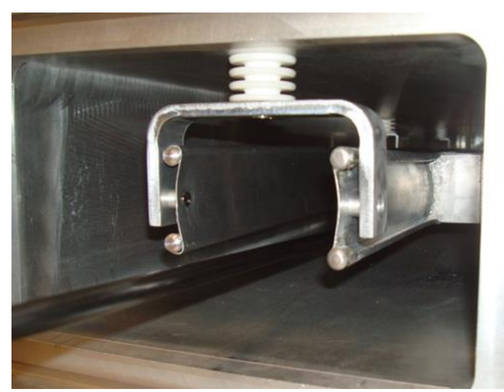
Old kick was too long and not strong enough



New Cornell Kicker

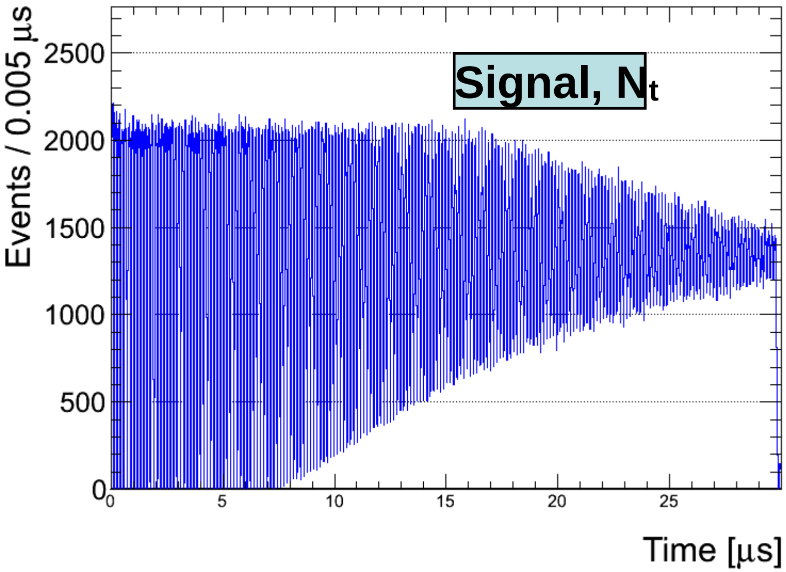


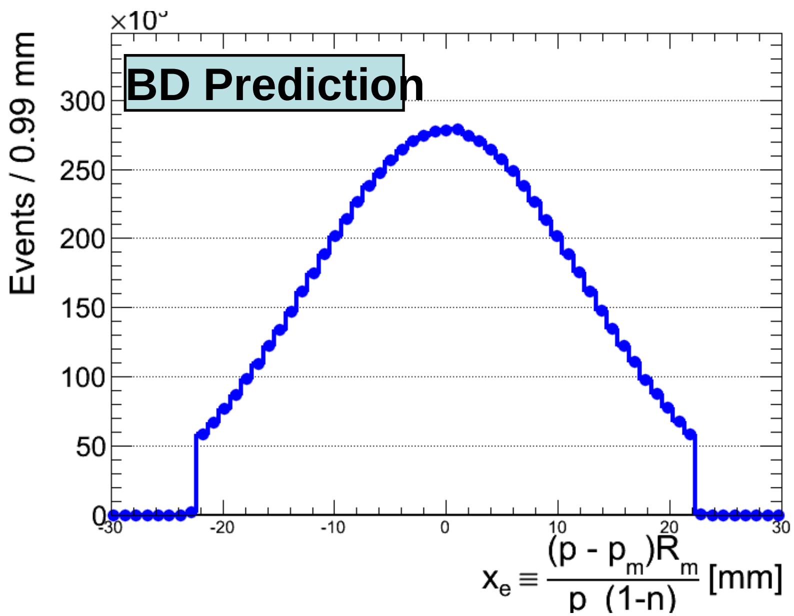




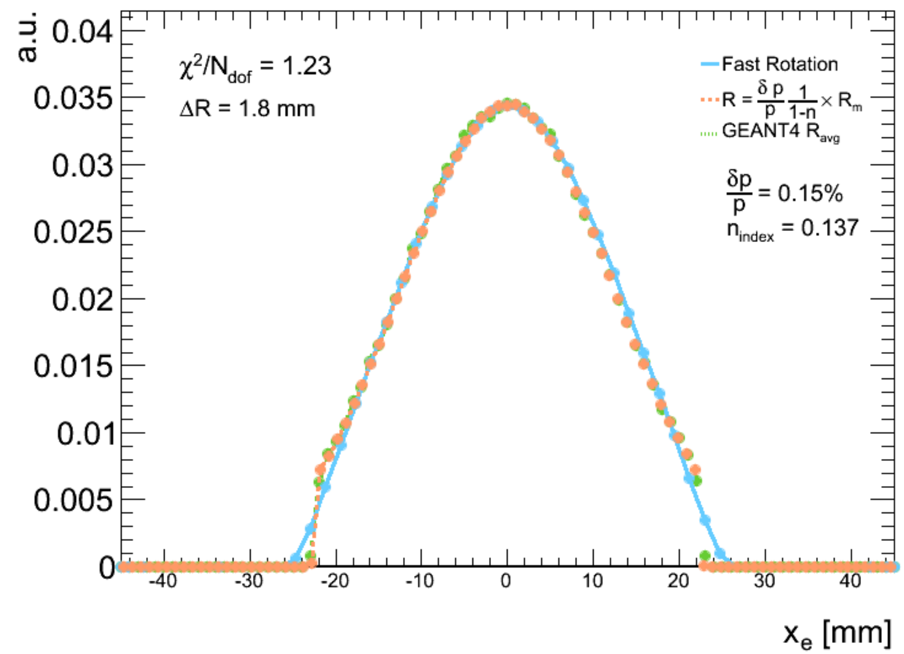
Sophisticated Modeling of beam, ring, decays

- **Example: Incoming bunched beam spreading and yielding radial distribution**





51 Radial bins

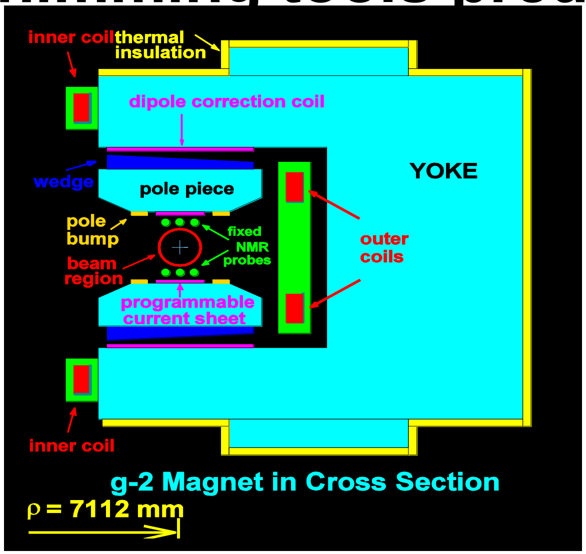


Fast Rotation

BD Prediction

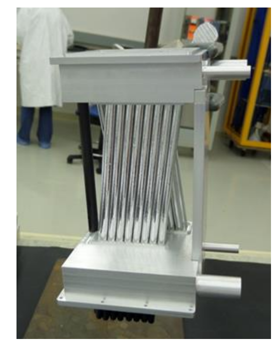
Brute Force GEANT

Higher (field) Uniformity: OPERA 3D and refined shimming tools predict improved intrinsic uniformity



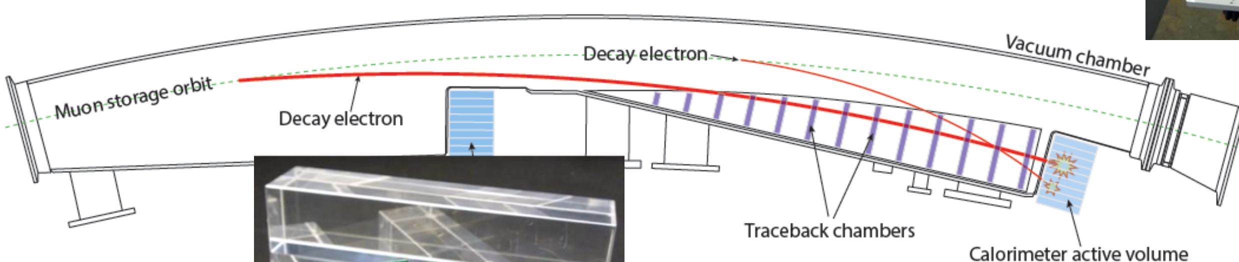
Plus:

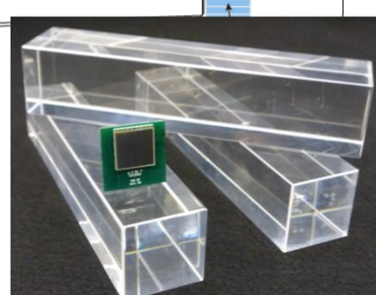
- Strict temperature stability of building
- Triple fixed NMR probes



Reduced Precession Systematics:

All new detectors, electronics & DAQ





E989 Collaboration: 38 Institutes; >150 Members

Domestic Universities
- Boston
- Cornell
- Illinois
- James Madison
- Massachusetts
- Mississippi
- Kentucky
- Michigan
- Michigan State
- Mississippi
- Northern Illinois University
- Northwestern
- Regis
- Virginia
- Washington
- York College

National Labs
- Argonne
- Brookhaven
- Fermilab

Consultants
- Muons, Inc.

Italy
- Frascati,
- Roma 2,
- Udine
- Pisa
- Naples
- Trieste

China:
- Shanghai

The Netherlands:
- Groningen

Germany:
- Dresden

Japan:
- Osaka

Russia:
- Dubna
- PNPI
- Novosibirsk

England
University College London
Liverpool
Oxford
Rutherford Lab

Korea
KAIST

FTE Committed

Survey of Collaboration for P5

Construction	Runnning	Analysis
2014 - 2016	2017-2018	2019 - 2022
91	80	68

Construction Funds (not ops)

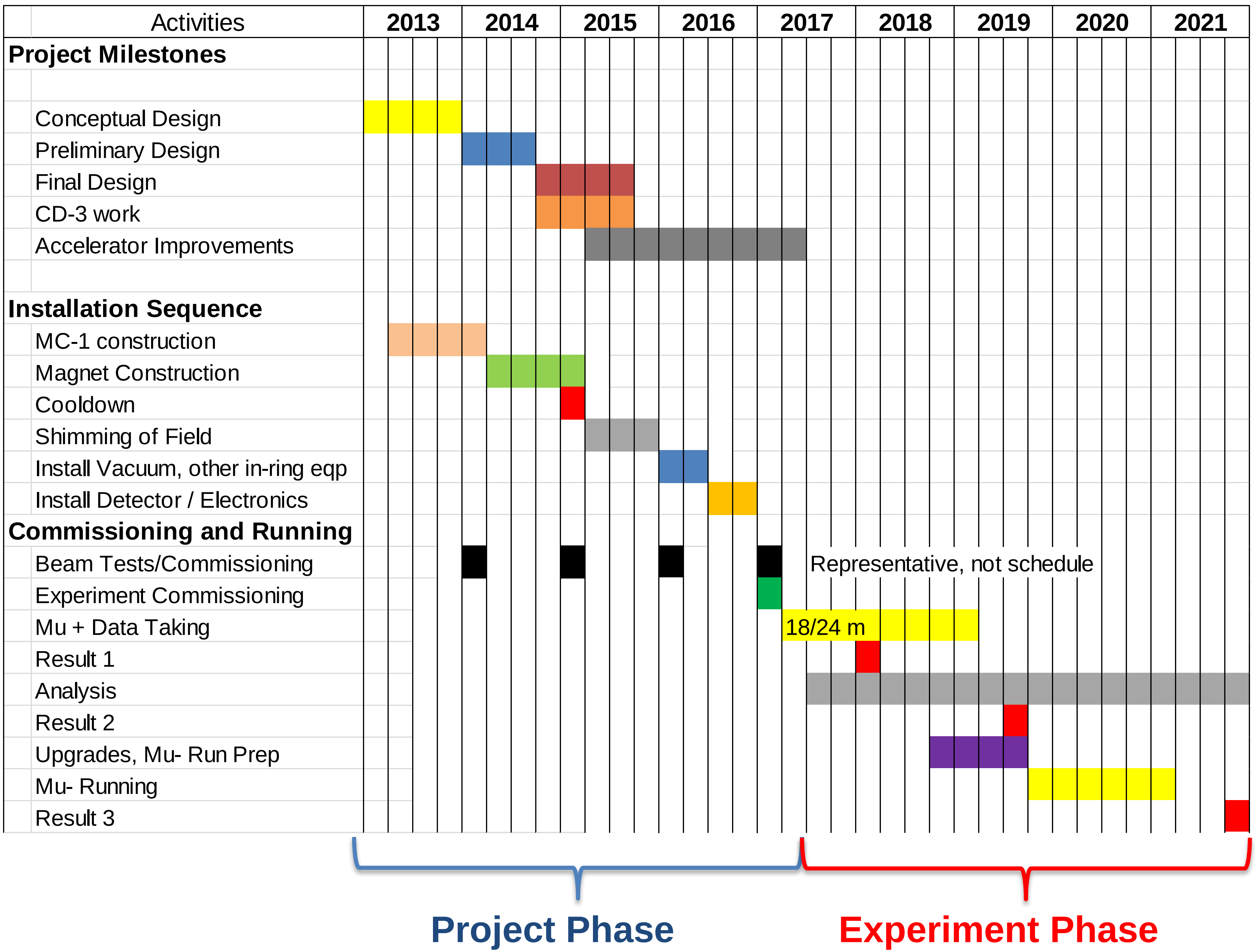
Source	$ M	Comment
DOE OHEP	46.4	CD-1 guidance; $9 M obligated; **$12 M contingency on remaining (40%)**
DOE Early Career	0.5	Casey: trackers ($2.5 M award)
NSF MRI	3.6	Consortium Proposal; Detectors; Electronics, DAQ, Including 30% match (mostly from Universities)
ITALY: INFN	0.40	Laser calibration
UK: STFC	0.40	Trackers, NMR
China: Shanghai	0.25	PbF2 crystals *
Texas Instruments	0.20	Digitizer chips*

Awarded

Additionally **E821 Components And most of the Pbar Complex**	**50 – 100 M**	**Storage Ring, Vacuum, Power supplies, Pbar (now muon) target system, Beamline elements, … Debuncher, etc etc,**

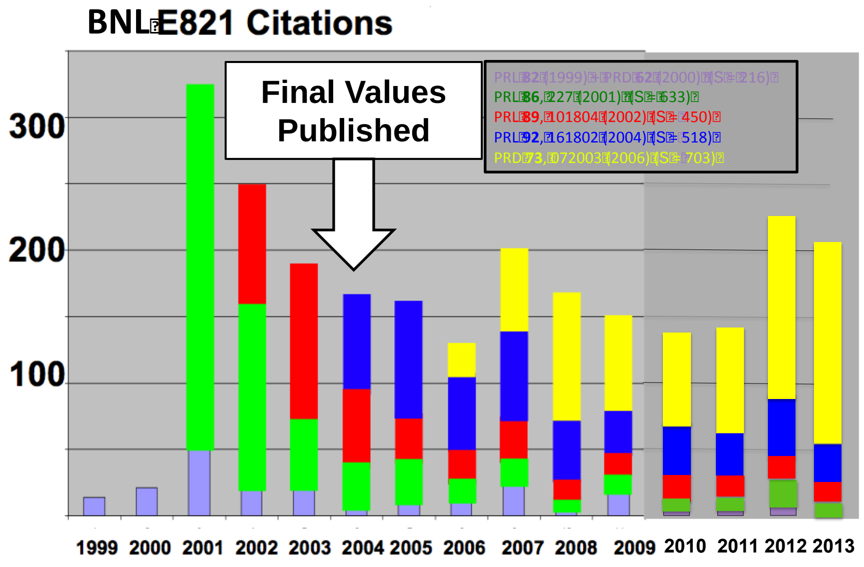
***part of MRI match formula**

Timeline


Activities
2013
2014
2015
2016
2017
2018
2019
2020
2021
Project Milestones
Conceptual Design
Preliminary Design
Final Design
CD-3 work
Accelerator Improvements
Installation Sequence
MC-1 construction
Magnet Construction
Cooldown
Shimming of Field
Install Vacuum, other in-ring eqp
Install Detector / Electronics
Commissioning and Running
Beam Tests/Commissioning
Experiment Commissioning
Mu + Data Taking
Result 1
Analysis
Result 2
Upgrades, Mu- Run Prep
Mu- Running
Result 3
Representative, not schedule
18/24 m
Project Phase
Experiment Phase

Muon g-2 Summary

- **Physics case compelling**.
  - *Is this new physics? What could it be telling us ?*
- **Project fine tuned and optimized**
  - Proven components
  - Experienced collaboration: New + Old
  - Timeline relevant to current physics priorities



Interest increasing

Backup

International Collaborators

Areas of contributions:

- **China:** Shanghai Jiaotong University awarded support for 20% of the Calorimeter Crystals
- **Italian groups** awarded 1st phase of funding from INFN for Laser Calibration
  - (Frascati, Roma 2, Pisa, Udine, Naples,* Trieste*)
- **British groups** awarded funding from SFTC for Tracker Development and Absolute Probe
  - Liverpool, UC London, Oxford
  - Others: RAL and Cockcroft under discussion
- **Korea** KAIST Beam dynamics; will contribute financially
- **Russia:** Dubna: DAQ visualiztion; Novisibirsk: running, analysis

DOE OHEP Provides

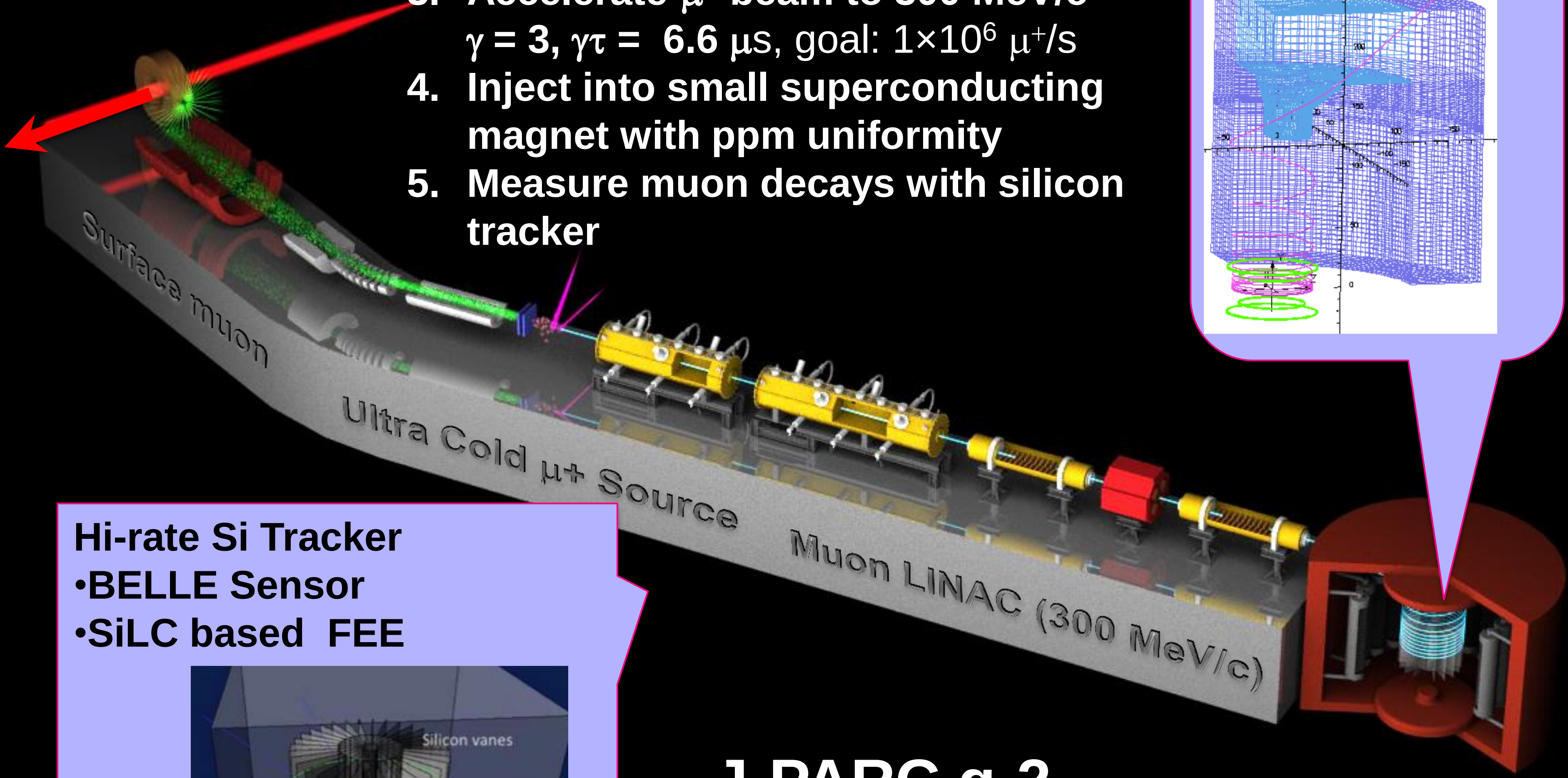
- Storage Ring Move
- Beamlines specific to g-2 (about half of budget)
- Ring assembly
- Kicker, Quad and Inflector upgrades
- Much of the Field work
- Some of the detector work
- Project Management

Rough Yearly Costs during Operations*

- **Assume accelerator complex is running**
  - We use 4/20 of protons, parasitic to neutrinos
  - We assume beamlines are supported Accelerator operations budget
- **What is specifically g-2? ~$1-2 M/year**
  - Cryogenics operations and cryogens
  - People / Visitors
  - Maintenance and modest Upgrades

***A matter of definitions of what is g-2 and what is lab operations in general**

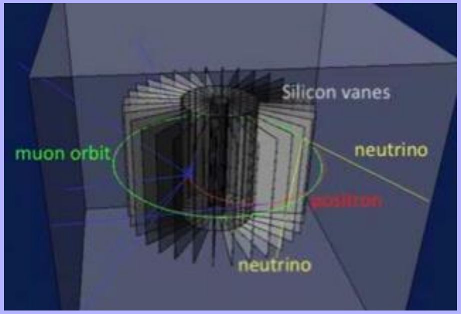
1. Form μ^+e^- atom with low-E μ beam
2. Photo-ionize muonium to produce low emittance μ^+ beam
3. Accelerate μ^+ beam to 300 MeV/c
   $\gamma = 3$, $\gamma\tau = 6.6\ \mu s$, goal: $1\times10^6\ \mu^+/s$
4. Inject into small superconducting magnet with ppm uniformity
5. Measure muon decays with silicon tracker



Precision Magnet and Beam Injection

Hi-rate Si Tracker

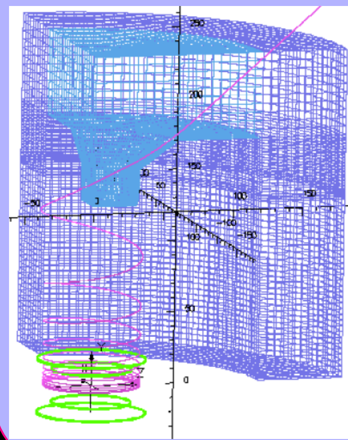
- BELLE Sensor
- SiLC based FEE

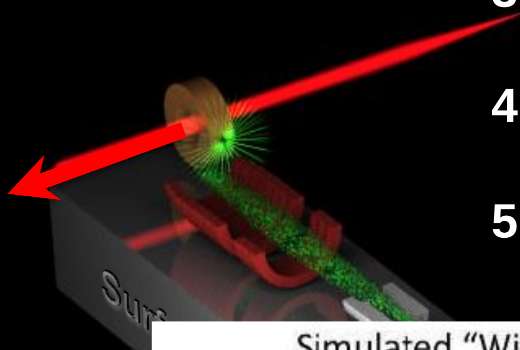


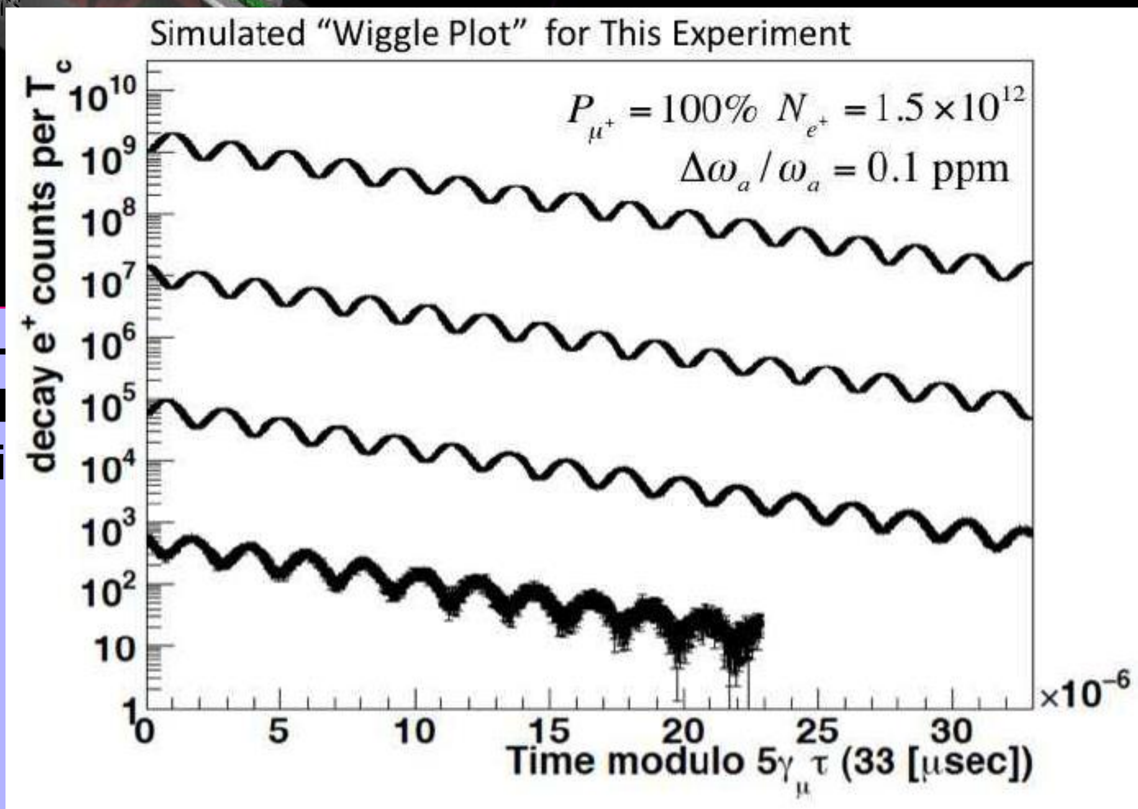
J-PARC g-2 Experiment

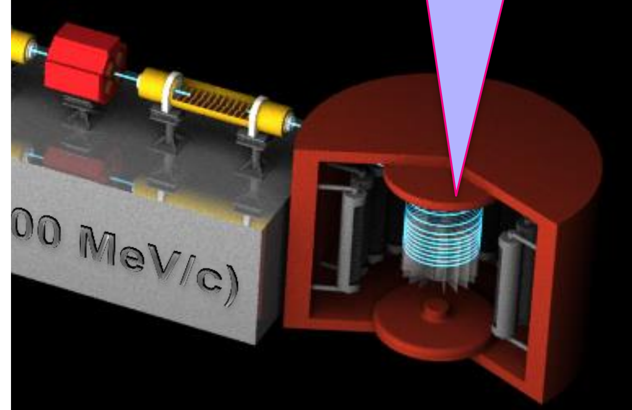
1. Form μ^+e^- atom with low-E μ beam
2. Photo-ionize muonium to produce low emittance μ^+ beam
3. Accelerate μ^+ beam to 300 MeV/c
   $\gamma = 3$, $\gamma\tau =$ **6.6** μs, goal: 1×10^6 μ^+/s
4. Inject into small superconducting magnet with ppm uniformity
5. Measure muon decays with silicon tracker

Precision Magnet and Beam Injection









Hi-
•Bl
•Si

What drives the design of the measurements?

Systematics on Precession

New detectors to mitigate

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Gain changes	0.12	Better laser calibration; low-energy threshold; temperature stability; segmentation to lower rates; no hadronic flash	0.02
Lost muons	0.09	Running at higher n-value to reduce losses; less scattering due to material at injection; muons reconstructed by calorimeters; tracking simulation	0.02
Pileup	0.08	Low-energy samples recorded; calorimeter segmentation; Cherenkov; improved analysis techniques; straw trackers cross-calibrate pileup efficiency	0.04
CBO	0.07	Higher n-value; straw trackers determine parameters	0.03
E-Field/Pitch	0.06	Straw trackers reconstruct muon distribution; better collimator alignment; tracking simulation; better kick	0.03
Diff. Decay	0.05[1]	better kicker; tracking simulation; apply correction	0.02
Total	0.20		0.07

Systematics on Field

Large number of small improvements

E821 Error	Size [ppm]	Plan for the E989 $g-2$ Experiment	Goal [ppm]
Absolute field calibrations	0.05	Special 1.45 T calibration magnet with thermal enclosure; additional probes; better electronics	0.035
Trolley probe calibrations	0.09	Absolute cal probes that can calibrate off-central probes; better position accuracy by physical stops and/or optical survey; more frequent calibrations	0.03
Trolley measurements of B_0	0.05	Reduced rail irregularities; reduced position uncertainty by factor of 2; stabilized magnet field during measurements; smaller field gradients	0.03
Fixed probe interpolation	0.07	More frequent trolley runs; more fixed probes; better temperature stability of the magnet	0.03
Muon distribution	0.03	Additional probes at larger radii; improved field uniformity; improved muon tracking	0.01
Time-dependent external B fields	–	Direct measurement of external fields; simulations of impact; active feedback	0.005
Others	0.10	Improved trolley power supply; trolley probes extended to larger radii; reduced temperature effects on trolley; measure kicker field transients	0.05
Total	0.17		0.07

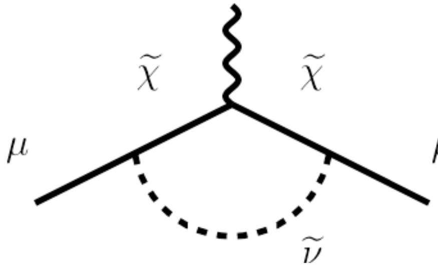
Overall, ω_p systematics need to be reduced by a factor of 2.5

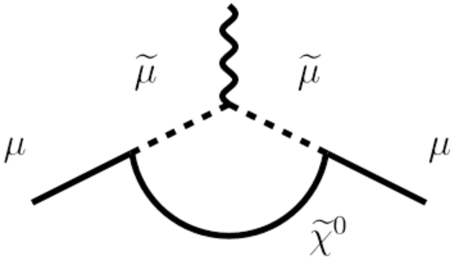
Hadronic Contributions on the Lattice

Blum, et al., arXiv:1311.2198v1 [hep-ph] 9 Nov 2013

- **Lattice**
  - **Lowest-order:** Taking into account current resources and those expected in the next few years, the lattice-QCD uncertainty on **a**(HVP), currently at the 5%-level, can be reduced to 1 or 2% within the next few years. … With increasing experience and computer power, it should be possible to compete with the $\mathbf{e^+e^-}$ determination of **a**(HVP) by the end of the decade
  - **HLBL: …** we emphasize that a lattice calculation with even a solid 30% error would already be very interesting. Such a result, while not guaranteed, is not out of the question during the next 3-5 years.

1 Example: SUSY contribution to a_μ :





Difficulty to measure at the LHC

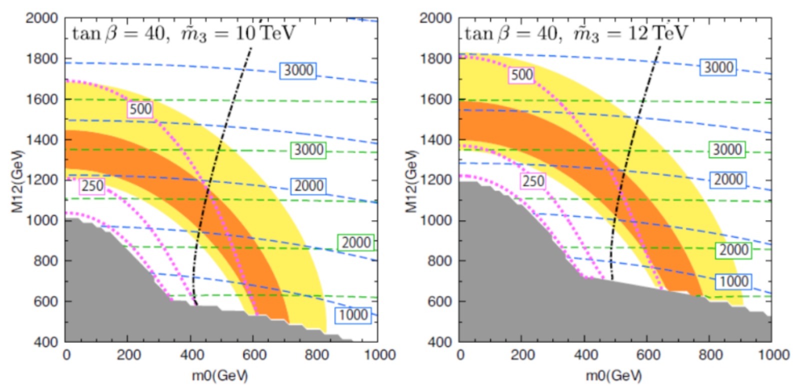
$$a_\mu^{SUSY} \approx 130 \times 10^{-11} \left(\frac{100\ \text{GeV}}{M_{SUSY}} \right)^2 \tan\beta \, \text{sign}(\mu)$$

Contrary to 1st impressions, LHC limits do not rule out supersymmetry

Example: split supersymmetry →

(and many others)

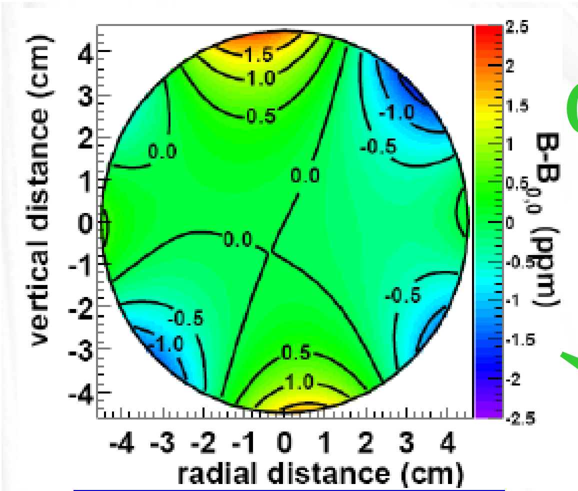
Muon g-2 and 125 GeV Higgs in Split-Family Supersymmetry



arXiv:1303.6995v1

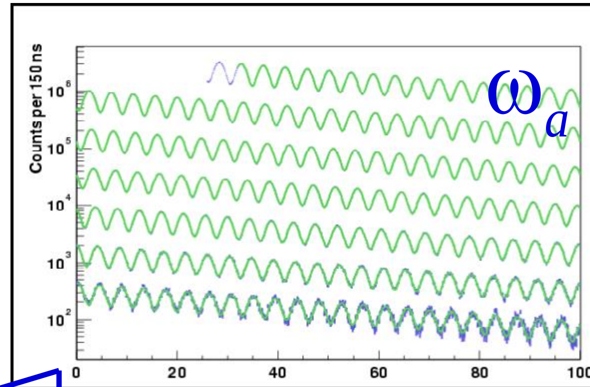
March, 2013

The muon anomaly is obtained from three well-measured quantities



ω_p

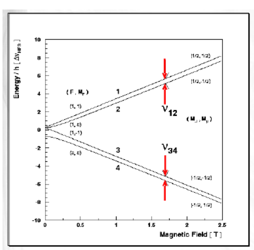
Our "Magnet"



ω_a

Our conventional Detector, Electronics, and DAQ systems

$$a_\mu = \frac{\dfrac{\omega_a}{\omega_p}}{\dfrac{\mu_\mu}{\mu_p} - \dfrac{\omega_a}{\omega_p}}$$



μ_μ/μ_p = 3.183 345 24(37) (120 ppb)

= *3.183 345 39(10) (31 ppb)*

External Muonium Hyperfine Expt.